FULL-SCALE AND LABORATORY FATIGUE CRACKING PERFORMANCE OF COMBINED HIGH-RECYCLE AND WARM MIX ASPHALT PAVEMENTS

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ABSRTACT

The Federal Highway Administration's Office of Infrastructure Research and Development has initiated a full-scale accelerated pavement testing experiment to evaluate the fatigue cracking performance of sustainable asphalt materials and mix designs. Recycled asphalt pavement (RAP) contents providing up to 40% asphalt binder replaced (ABR) by 44% by RAP by weight have been incorporated in hot mix asphalt (HMA) production as well as reduced-temperature warm mix asphalt (WMA) that was produced with water foaming and chemical additive. Recycled asphalt shingles (RAS) have been incorporated to provide 20% ABR in HMA. The objective of the experiment is to establish realistic boundaries for high-RAP & RAS mixtures employing WMA technologies based on percent binder replacement and binder grade changes when combined together. This paper will document the construction, the as-built engineering properties of the 10 different test sections characterized in the laboratory, and the full scale fatigue cracking performance.

INTRODUCTION

Established in 1986, the Pavement Testing Facility (PTF) at Turner Fairbank Highway Research Center (TFHRC) of Federal Highway Administration (FHWA) provides pavement researchers and engineers with the capability to simulate an entire service life of full scale pavements in just a few months. The PTF is an outdoor laboratory featuring two Accelerated Loading Facility (ALF) units. Each ALF unit has a moving trolley that closely reproduces the conditions of one half of a single truck axle with various tire configurations (super single or standard dual). The trolley speed can be varied up to 11 miles per hour (18 kilometers per hour), and wheel load levels can be adjusted from 10,000 pounds to 23,000 pounds. The PTF can accommodate up to 12 full scale ALF pavement test lanes and each lane is further divided into four test sites furnishing a total of 48 potential case studies. Two ALF units allow simultaneous testing of two pavement lanes (sites) under the same ambient temperature and moisture conditions or at the same pavement age.

In October 2013, PTF completed a construction of the test lanes to study the combination of two sustainable technologies: (1) increased use of recycled materials in roadways and (2) reduced-temperature warm-mix asphalt. The full scale test lanes were constructed with varying degrees of recycle content using alternative production technologies that are more environmentally friendly than previous techniques. FHWA will test the sections to failure through 2015 to establish realistic boundaries for mixtures with high amounts of recycle content that employ warm-mix asphalt production technologies. This research is also going to identify optimal pairings of the two technologies, while ensuring that they have limited or no impact on performance compared to conventional pavement materials.

This paper summarizes the construction, the as-built engineering properties of the 10 different ALF lanes characterized in the laboratory, and some preliminary data collected from the full scale fatigue cracking performance tests.

EXPERIMENTAL DESIGN

The experimental design developed in this study is summarized in Table 1. Based on this design, ten plant-produced asphalt mixtures are characterized through a series of small laboratory tests, and their structural response and fatigue cracking performance are evaluated on the full scale ALF lanes. To implement this testing program, two commonly used asphalt binders in the State of Virginia were chosen as virgin binders (PG 64-22 and PG 58-28) that were combined either with recycled asphalt pavement (RAP) or with recycled asphalt shingles (RAS).

RAP contents providing 20% asphalt binder replaced (ABR) by 23% by RAP by weight and 40% ABR by 44% by RAP by weight have been incorporated in hot mix asphalt (HMA) production as well as reduced-temperature warm mix asphalt (WMA). Either water foaming or chemical additive (Evotherm™) was used to produce WMA. For RAS mixes, RAS content that provides 20% ABR by 6% by RAS by weight was introduced only in HMA. With this comprehensive experimental study, FHWA may find clear answers to the combined effect of high-recycle and WMA materials on the engineering properties and fatigue cracking performance.

Table 1.
Experimental Design.

ALF Lane	% ABR[a]		Virgin Binder	Production Temp.	WMA Process
	RAP	RAS			
1	0	-	64-22	300F-320F	-
2	40	-	58-28	240F-270F	Water Foam
3	-	20	64-22	300F-320F	-
4	20	-	64-22	240F-270F	Evotherm[b]
5	40	-	64-22	300F-320F	-
6	20	-	64-22	300F-320F	-
7	-	20	58-28	300F-320F	-
8	40	-	58-28	240F-270F	Evotherm[b]
9	20	-	64-22	240F-270F	Water Foam
10	40	-	58-28	300F-320F	-

[a]asphalt binder replacement
[b]chemical additive

CONSTRUCTION OF ALF TEST LANES

Construction of ALF test lanes at PTF started in July 20 of 2014 and ended in October 29 of 2014. It began with the milling of existing asphalt layers on the parking lot and the ALF lanes shown in Figure 1. The parking lot was used for 2-inch thick asphalt test strips. Each ALF lane was designed to have a new 4-inch thick (two 2-inch lifts) asphalt layer placed on top of a 22-inch thick Crushed Aggregate Base (CAB) and a silt clay subgrade (American Association of State Highway and Transportation Officials (AASHTO) soil classA-4). Therefore, in some lanes whose asphalt layers had been thicker than 4 inches for previous studies, a new base material (25 mm Nominal Maximum Aggregate Size (NMSA)) was added to adjust the level of CAB. In addition, top portion (about 4-inch deep) of CAB was reconditioned and compacted to ensure the uniform support from CAB. A soil Light Weight Deflectometer (LWD) with a 300 mm loading plate was utilized to check the modulus of finished CAB. Figure 2 presents the average modulus of CAB in each ALF lane.

Figure 1.
Aerial Image of ALF Reconstruction Area at TFHRC.

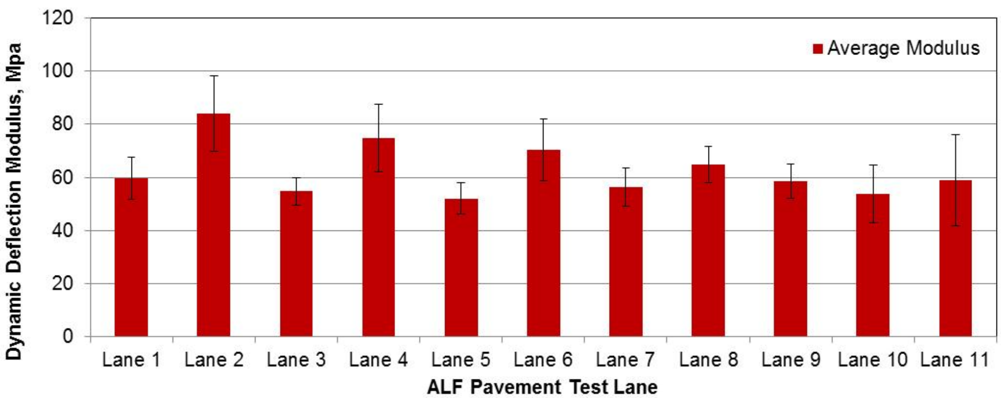


Figure 2.
Modulus of Finished CAB (lane 11 is a reproduction of lane 10).

For quality acceptance of asphalt layers, a test strip was built before each ALF asphalt layer was placed. This strip was used to determine the appropriate rolling pattern needed to achieve the desired in place density, to check the uniformity of layer thickness, and to approve each asphalt mixture by determining its asphalt binder content, aggregate gradation, maximum specific gravity, and volumetrics. The same quality acceptance test was also performed on all ALF lanes as illustrated in Figure 3. The paving contractor and FHWA randomly obtained four bucket samples of each plant-produced mixture according to AASHTO T168. The materials had to meet the specifications before the ALF pavement could be built.

In this study, a half-inch (12.5 mm) Nominal Maximum Size of Aggregate (NMSA) was used for all asphalt layers as shown in Figure 4. Density and thickness were checked both by sawing rectangular blocks and by coring cylindrical samples from the pavement. Layer thickness was measured at each survey nail. Figure 5 presents the average thickness of each lane.

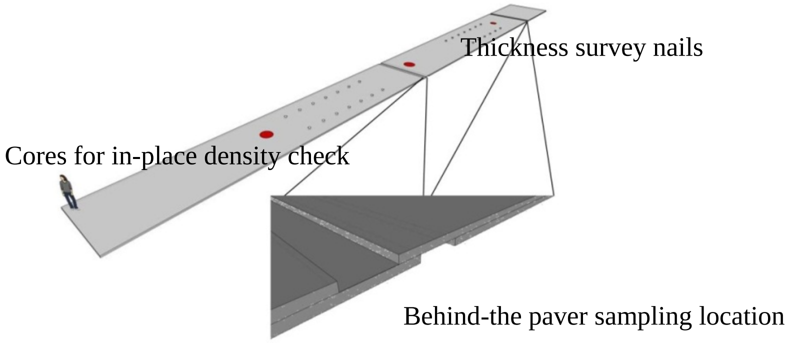


Figure 3.
Sampling and Surveying Scheme for Quality Acceptance Test.

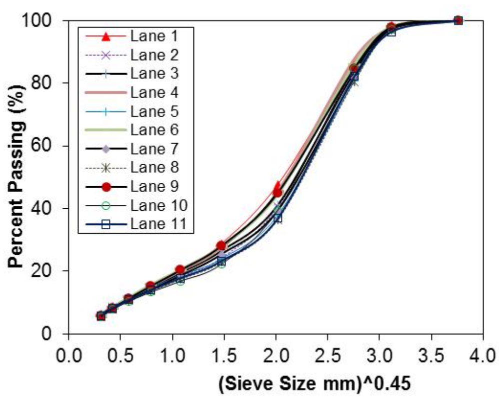


Figure 4.
Target Aggregate Gradation of ALF Test Lanes (lane 11 is a reproduction of lane 10).

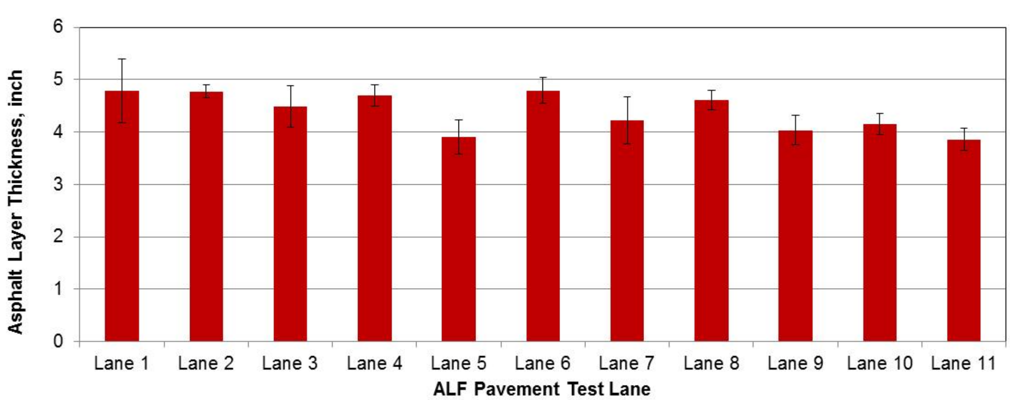


Figure 5.
Asphalt Layer Thickness of ALF Test Lanes (lane 11 is a reproduction of lane 10).

All quality acceptance test data were collected, analyzed and summarized in the “spider web” charts as shown in Figure 6. Prepared for all test strips and ALF lanes, these charts enabled paving contractor to overview and improve the quality of construction and materials designed and produced. Specifications were tight and thus some mixtures in the test strips were rejected in order to get them produced correctly. Among ALF test lanes only lane 10 was rejected. However, instead of removing that lane, it was decided to keep it for additional performance at the final stage of the project. The rejected mixture (40% ABR RAP) originally assigned for lane 10 was redesigned and placed on lane 11. As a result of the reconstruction, 16 test strips and 11 ALF test lanes were built at the PTF.

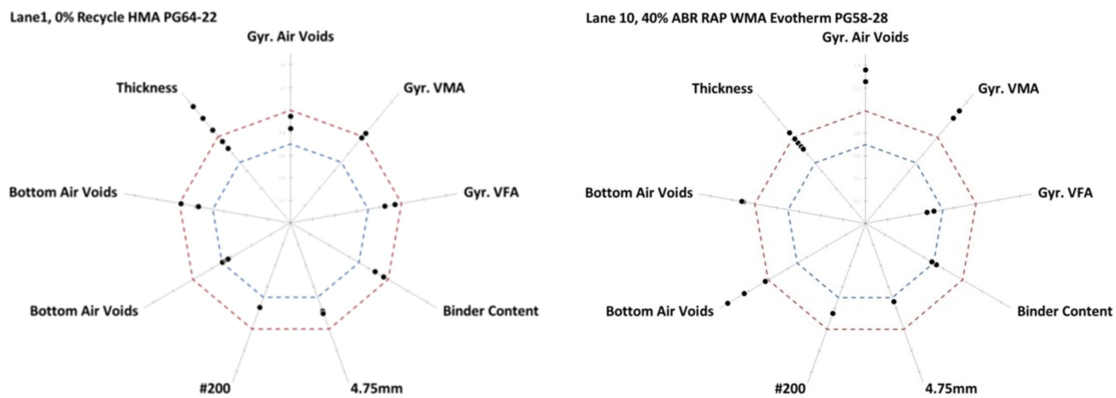


Figure 6.
Quality Acceptance Result of ALF Lane 1 (Accepted) and Lane 10 (Rejected).

LABORATORY CHARACTERIZATIONS OF RECYCLE MIXTURES

To characterize RAS and RAP, both binder extraction and performance grade evaluation tests were conducted on samples taken from RAP and RAS stockpiles. The RAP and the RAS were sampled according with AASHTO T168 (Sampling of Bituminous Paving Mixtures). First, the materials were dried in the oven at 110°C until constant weight in order to remove the moisture. The asphalt material contained in the samples was extracted, recovered and the rheological properties were investigated. The extraction method was based on the AASHTO T319-08 (Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures), while the solvent of choice was trichloroethylene. In brief, the procedure involved soaking the materials with solvent for about 40 minutes, followed by the removal of the saturated solvent. Two more subsequent washes were necessary to remove all the asphalt material and to obtain a light brown color for the final filtrate. About 2 liters of solvent are considered enough for the extraction of about 5kg of recycled RAP or RAS. The filtrate was passed through a centrifuge and then through a super-centrifuge to remove all the traces of fines. The remaining aggregates (for RAP) or fibers and fines (for RAS) were dried and then weighted. The percent difference between the initial weight and the weight after the extraction procedure represents the asphalt cement (AC) content. A total of 13 RAP and 6 RAS extractions were performed. Table 2 presents the average AC percent in the extracted materials.

Table 2.Average Asphalt Cement (AC) Content (%) in RAP and RAS Materials.

Materials	Average AC[a], %
RAP	4.72
RAS	20.85

[a]ignition oven test yielded slightly higher average AC % values (5.28% for RAS and 22.45% for RAS)

The solvent containing extracted binders was removed with the use of a rotary evaporator. The procedure was performed at 135°C under protected conditions (a blanket of CO_2 gas and a mild vacuum of 5in Hg). At the end, for a short period of time (15min) an increase in vacuum to 20in Hg was assumed to eliminate all traces of solvent. The extracted asphalts were tested for conventional binder rheology. Mixture preparation, mixture aging and the recovery procedure involved the exposure of the materials at high temperatures for extensive periods of time. It may be correct to assume that the recovered asphalt aging level was at least at the Rolling Thin Film Oven (RTFO) level or higher. As a consequence, no specific procedures were used to further age the extracted materials. Low, Intermediate and High Temperature Performance Grades (LTPG, ITPG and HTPG respectively) were determined according to the AASHTO standards (T-313-12, Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR) and T 315-12, Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)). Some pertinent properties of the extracted AC from the RAP material are presented in Table 3.

Table 3.Pertinent Properties of the Extracted AC from the RAP Material.

Binder Performance Grade	Temperature,°C
High Temperature Performance Grade (HTPG)	89.4
Intermediate Temperature Performance Grade (ITPG)	29.1
Low Temperature Performance Grade (LTPG)	-21.7

The asphalt binder obtained from RAS was extremely stiff and subsequent attempts to test it in DSR have failed to provide a meaningful result. It is fair to say that the High Temperature Performance Grade (HTPG) was above 140°C, exceeding the normal DSR testing range. Because of the nature of the material, no attempt was done to investigate other rheological properties.

Dynamic modulus, phase angle, and time-temperature shift factor are the fundamental engineering properties of asphalt mixtures, which have also been used as key variables for performance prediction models. To obtain those properties from control and recycle mixes, a series of complex modules tests was performed in the laboratory. These tests were conducted at multiple frequency-temperature combinations that were determined to be adequate to develop a dynamic modulus master curve. The Asphalt Materials Performance Tester (AMPT) was used for the tests and data analyses, and small scale cylinder samples were extracted from top and bottom lift of 6 inch diameter field cores that were taken from each ALF lane. The testing frequencies range from 0.1 to 25 Hz and the testing temperature from 4.4 to 54.4°C. To minimize any permanent deformations, testing was conducted with temperatures starting from the lowest to the highest, and frequencies were applied at each temperature from the fastest to the slowest.

The load amplitude was adjusted based on the material stiffness, air void content, temperature, and frequency to keep the strain response with 85-115 µstrains (NCHRP 9-29 default values).

Figure 7 presents the dynamic modulus (|E*|) master curves. The dynamic moduli measured from top and bottom lift samples were averaged for this presentation. Overall, dynamic modulus of lane 1(0% RAP, PG 64-22 HMA), a control mix, was the smallest and dynamic modulus of lane 5 (40% RAP, PG 64-22 HMA) was the largest. To better understand the effect of recycle content on dynamic modulus, only lanes 1, 3 (20% RAS, PG 64-22 HMA), 5, and 6 (20% RAP, PG 64-22 HMA) were plotted in Figure 8. The ranking of the dynamic modulus from high to low was lane 5, lane 3, lane 6, and lane 1. This suggested that asphalt mixture becomes stiffer as recycle content increases. As many fatigue prediction models suggest, a higher dynamic modulus normally causes a shorter fatigue life. Although other model variables need to be considered for more accurate assessment, it would be fair to say that high recycle content could make asphalt material more vulnerable to fatigue cracking.

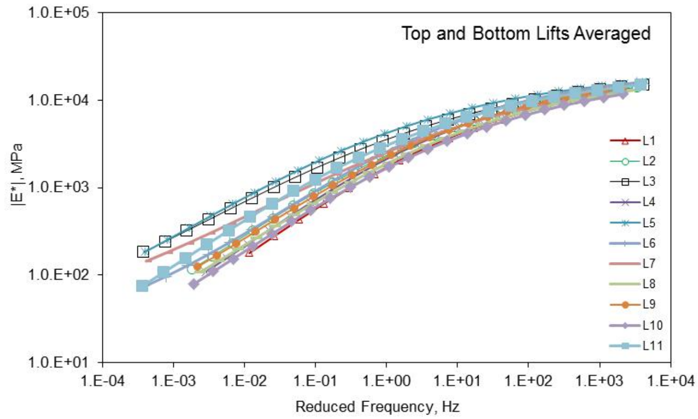


Figure 7.
|E*| Master Curves of All Control and Recycle Mixtures in Log-Log Scale

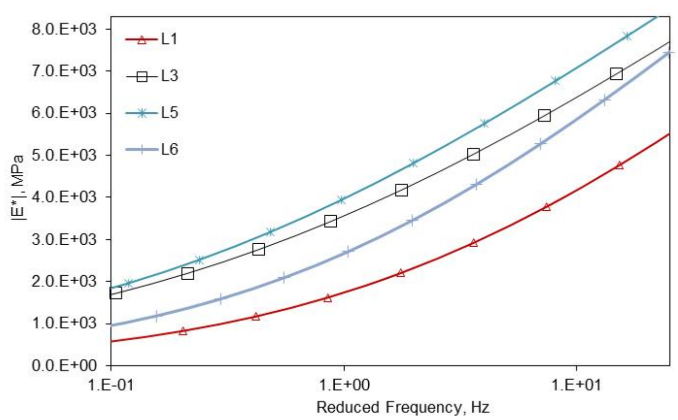


Figure 8.
Effect of Recycle Content on |E*| (Bottom Lift)

Figure 9 illustrates the effect of soft virgin binder (PG 58-28) on the dynamic modulus. The dynamic moduli of recycle mixtures of lanes 1, 6, 7 (20% RAS ABR, PG 58-28 HMA), and 8 (40% RAP, PG 58-28, HMA) were compared. As already seen in Figure 7, three mixtures with RAP or RAS had higher dynamic moduli than that of conventional HMA (lane 1). However, soft binder seemed effective in reducing the dynamic moduli of recycle asphalt mixtures and thus increasing the fatigue life even at the higher recycle level (40% ABR RAP).

Finally, the effect of WMA on the dynamic modulus was investigated at the same recycle content level (20% ABR RAP). Figure 10 shows dynamic moduli of WMA were smaller than that of HMA. This may be due to the amount of aging induced during the mixture production and suggests WMA should provide a better performance than HMA counterpart among recycle mixtures. The effect of WMA technologies (water foam versus chemical additive) was not significant.

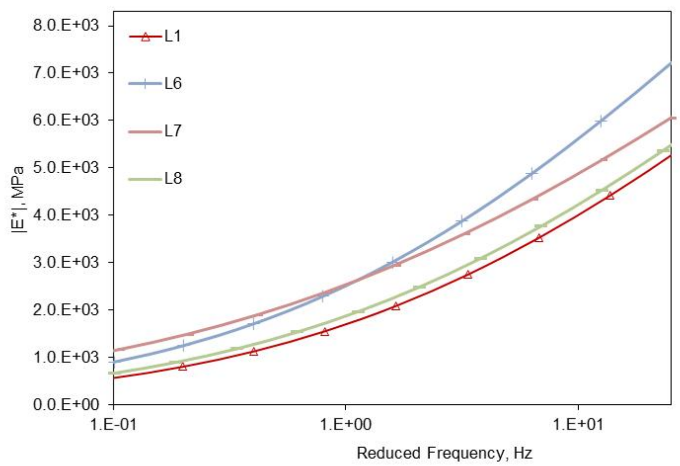


Figure 9.
Effect of Soft Binder on |E*| (Top Lift)

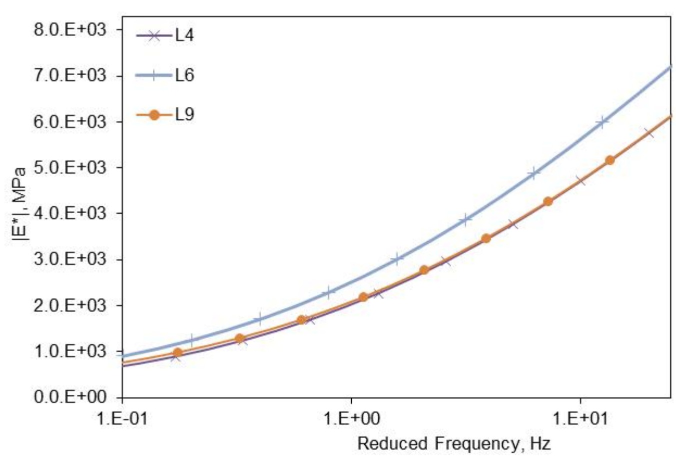


Figure 10.
Effect of WAM on |E*| (Top Lift)

After the complex modulus test, the fatigue test was conducted on both small scale field samples and standard gyratory samples using the AMPT. Air void content of gyratory samples was controlled at around 7.0% to simulate the target field air void and the tests were carried out at 20^{o}C until each specimen completely failed. Table 4 summarizes the fatigue performance of individual mixtures. Three performance groups were formed: green (better performance), yellow (intermediate performance) and red (worse performance). Asphalt mixtures used for the construction of ALF lanes 1, 8, 9, and 10 were categorized into the green group, whereas mixtures for lanes 3, 5, 7 were into the red group. This is in good agreement with the fatigue performance ranking estimated based on the dynamic modulus master curves described earlier. Except for 20% ABR RAP PG 64-22 WMA, both field and gyratory samples yielded the same fatigue performance.

Table 4. AMPT Fatigue Test Results.

	Horizontal Field Core In-Place Density	Standard Gyratory Sample Controlled 7% air voids
GREEN	0% Control PG 64-22 40% ABR RAP PG 58-28 20% ABR RAP PG 64-22 WMA Foam 40% ABR RAP PG 58-28 WMA Chem. #1	0% Control PG 64-22 40% ABR RAP PG 58-28 20% ABR RAP PG 64-22 WMA Chem. 40% ABR RAP PG 58-28 WMA Chem. #1
YELLOW	40% ABR RAP PG 58-28 WMA Foam 20% ABR RAP PG 64-22 WMA Chem. 20% ABR RAP PG 64-22 40% ABR RAP PG 58-28 WMA Chem. #2	40% ABR RAP PG 58-28 WMA Foam 20% ABR RAP PG 64-22 WMA Foam 20% ABR RAP PG 64-22 40% ABR RAP PG 58-28 WMA Chem. #2
RED	20% ABR RAS PG 64-22 20% ABR RAS PG 58-28 40% ABR RAP PG 64-22	20% ABR RAS PG 64-22 20% ABR RAS PG 58-28 40% ABR RAP PG 64-22

ALF LANE INSTRUMENTATION AND DATA ACQUISITION

Each full scale test lane was 50 m by 4 m (165 feet by 14 feet) which was further divided into four sites. Immediate before the ALF fatigue testing, seven Layer Deflection Measurement Assemblies (LDMAs) were installed in each site to collect vertical deflections at the surface of asphalt layer and at the surface of underlying CAB. At each “milestone” (for instance every 25,000 load repetition), a survey rod was placed on each LDMA and vertical settlements were viewed and measured with a telescope fixed at a certain location throughout the testing. This information was used to quantify the rut depths and estimate the contributions of underlying layers. Also, a semi–automatic laser surface profiler was used to measure transverse pavement surface profile to support the LDMA measurements.

On each site, twelve K-type thermocouples were also installed at the designated locations and depths to collect pavement depth temperature (at surface, ¾ -inch, 2-inch, and 3¾-inch) and to control pavement zone temperature (at 2-inch). An electronic temperature control and data acquisition system was utilized to record the temperatures at various locations and depths in real time and to regulate the radiant heaters that provide a target zone temperature. Usually, the zone temperature is set at 19~20^{o}C for fatigue cracking can be increased up to 74^{o}C for high temperature rutting. Figure 11 depicts LDMA and thermocouple instrumentation.

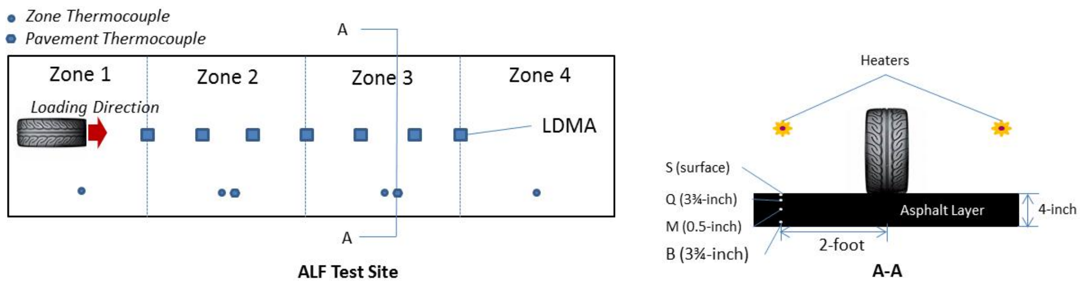


Figure 11.
ALF Test Site Instrumented with Thermocouples and LDMAs.

During the placement of asphalt layers on lanes 9 (site 2) and 10 (site 1), eleven strain gauges with three different types were installed. However, three longitudinal strain gauges did not survive the construction due to thin asphalt lift (2-inch) and heavy roller compactors. Strain responses from survived strain gauges were measured using a multi-channel data acquisition system before any fatigue loading began and are going to be predicted by the linear viscoelastic analysis for critical damage to establish relationships between response, axle loads, and pavement performance after considering the effect of climate and aging.

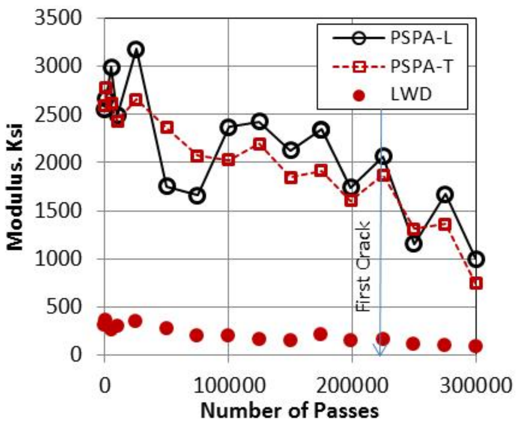
ALF FATIGUE TESTING

The frequency of load passes was used as a primary way of accelerating the fatigue cracking in recycled asphalt pavements, whereas wheel load and pavement temperature conditions were maintained the same throughout the testing. Pavement temperature was conditioned at 20^{o}C so that no high temperature rutting occurred. The wheel load was 14,200 pounds and was applied in a unidirectional mode. As the loaded wheel travelled over the test site at a constant speed of 11 miles per hour, it followed a left-to-right wander pattern to simulate the lateral distribution of road way traffic. The moving trolley was fitted with a super single tire (HTR2 425/65R22.5) whose pressure was 100 psi (689 kPa).

Prior to the main fatigue test, a shakedown test was conducted on lane 9 (site 2) to estimate the speed of damage accumulation and the initiation time of macro-cracks. This shakedown test was also used to check the operation and data acquisition systems. The wheel load was 10,300 pounds in the beginning and was increased to 14,200 pounds after 125,000 passes because researchers at TFHRC felt that the 10,300-pound of wheel load was too light to induce cracking in a reasonable amount of time. Currently, main fatigue cracking tests are being conducted at lane 11 (site 2) and lane 1(site 2) with the 14,200 pounds of the wheel load.

The moduli of asphalt layers were measured at each milestone using an asphalt LWD with a 30 mm loading pin and a Portable Seismic Pavement Analyzer (PSAP) to monitor the modulus changes and to associate them with the damage accumulation. Both modulus tests were conducted at LDMA locations of each site, and PSPA test was conducted in longitudinal (PSPA-

L) and transverse (PSPA-T) directions. Figure 12 depicts the moduli measured at lane 9 and lane 11. No modulus and fatigue data were available on lane that has been subjected to only 5,000 loading passes. The moduli decreased as the number of loading passes increased, suggesting damages were gradually accumulated in asphalt layers. The first surface macro-cracks were observed about at 225,000 passes on lane 9 and 75,000 passes on lane 11.



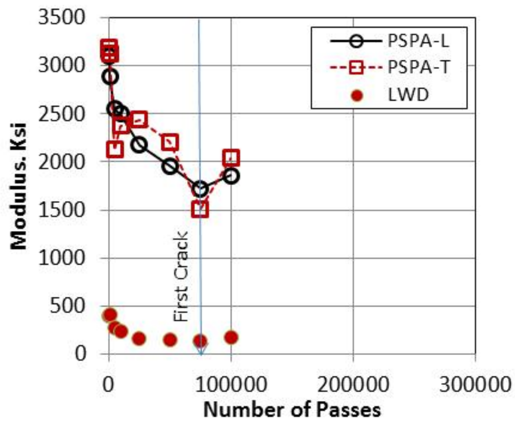
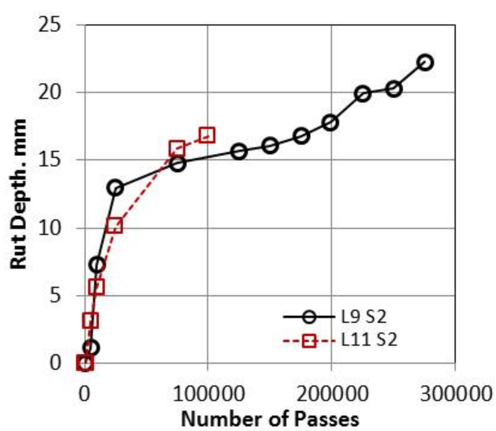


Figure 12.
Modulus Change in Lane 9 (left) and Lane 11 (right).

Rut depth and cracks were also measured manually on both lanes (sites). As illustrated in Figure 13, rut depths increased fast up to certain load cycle and gradually increased thereafter until the end of test. Crack surveys usually consisted of a manual measurement of cracks along the wheel track and characterization of extent and severity. Crack maps were sketched at each milestone and documented on transparent plastic sheet (Mylar® sheet). Figure 14 presents the accumulative crack lengths. So far, forensic study indicates most of cracks initiated at the bottom of asphalt layer and propagated upward (i.e., bottom-up cracking).



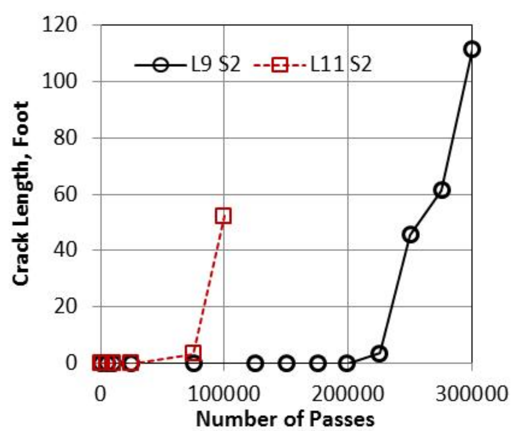


Figure 13.
Rut Depth in Lane 9 and Lane 11.

Figure 14.
Fatigue Cracking in Lane 9 and Lane 11.

SUMMARY

- In general, increasing recycle content stiffened the mixes and could shorten the fatigue life of recycle mixes

- Among virgin asphalt binders, the softer one (PG 58-28) that is one grade lower on both the high and low end softened the high ABR mixes and the RAS mix

- Reduced temperature WMA seemed to help reduce the stiffness of the 20% ABR RAP mixtures, but this effect was less clear at 40% ABR RAP.

- AMPT fatigue performance results were in good agreement with the fatigue life ranking estimated based on dynamic modulus master curves.

- Full scale fatigue performance is being evaluated using two ALF units with 14,200 pounds of wheel loads at 20^{o}C after a shakedown test. As more date become available, correlation between full scale performance and laboratory performance can be made to provide realistic boundaries for high-RAP & RAS mixtures employing WMA technologies.

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